# FAR INFRARED RESPONSE OF POINT-CONTACT JOSEPHSON JUNCTIONS

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We have measured spectral-response curves of superconducting point contacts suggesting the existence of frequency-dependent Josephson current amplitudes peaking in the vicinity of the energy gap. These point-contact Josephson junctions respond sensitively and with high speed to millimeter and submillimeter radiation. Radiation emitted to free space by one such junction was detected by another junction.

We have used superconducting point contacts, which show zero-voltage Josephson current[1,2] in their *V-I* characteristics, to study the response of Josephson current to radiation at frequencies in the vicinity of the energy gap, $2\Delta$. Our experiments show strong peaking of this response at frequencies close to, but not identical to, the gap. The easily fabricated point-contact form of junction used in these experiments couples more strongly than film junctions[3] or thin film bridges[4] to high-frequency radiation, as is apparent from the work of Dayem and Grimes.[5] A consequence of this strong coupling is that these junctions perform as sensitive, broadband, high-speed detectors of millimeter and submillimeter radiation. Though exact comparisons are difficult, the peak sensitivity of these junctions appears to be one to two orders of magnitude greater than that of existing helium-temperature far-infrared detectors.

The junctions were made by pressing together the ends of two pieces of 30-mil wire, one of which was flattened and the other sharpened by filing or by cutting with a razor blade. The *V-I* curve of the junction was adjusted as desired while immersed in liquid helium by varying the contact pressure. The spectral response of junctions formed of In-In, Pb-Pb, Nb-Nb, and Nb-Ta wires was studied by using the junctions as detectors in a far-infrared Fourier-transform spectrometer.[6] The spectrometer consisted of a Michelson interferometer, one arm of which was adjustable, which was illuminated by broadband radiation from a mercury arc lamp. On leaving the interferometer, the light was chopped and focused into a light pipe. The adjustable point contact was mounted transversely across a conical constriction at the bottom of the light pipe and was immersed in liquid helium.

The radiation falling on the junction diminished the maximum zero-voltage Josephson current that could flow through it, and shifted the whole *V-I* curve toward lower current. By using constant current bias to a point of high differential resistance in the *V-I* curve, a voltage at the chopper frequency was developed across the junction and served as the detector output. A lock-in amplifier synchronized to the chopper frequency amplified the signal and drove a strip-chart recorder on which the interference pattern was plotted as a function of the path difference in the Michelson interferometer. The spectral response of the detector was obtained by a standard procedure[6] from the interference pattern by computing its Fourier transform on a digital computer.

The spectrum for a typical In-In junction is shown in Fig. 1. Note that the response has a peak at 5.4 $cm^{-1}$; the tunneling energy gap for In at this temperature is $2\Delta = 7.2$ $cm^{-1}$. There is appreciable response extending up to about twice the peak frequency, which is well beyond the energy gap. This behavior was characteristic of all In-In junctions. At

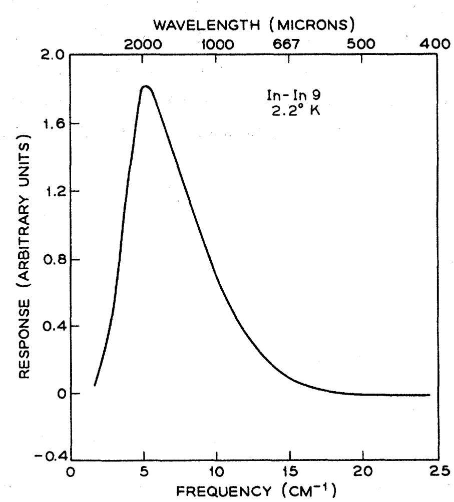


FIG. 1. Spectral response of a typical In-In superconducting point contact.

lower temperatures the peak sharpened somewhat; the $Q$ of the response increased.

The spectrum of a typical Nb-Nb junction is shown in Fig. 2. All Nb-Nb junctions behaved similarly. The energy gap of Nb is much larger than that of In; so the response extending to much shorter wavelengths was expected. However, the peak response is not near $2\Delta$. Rather there is pronounced dip in the response at 24 $cm^{-1}$ which is approximately equal to the energy gap ($2\Delta = 22$ $cm^{-1}$). Dips also appear at about $\Delta/2$, $\Delta$, and $3\Delta$. We do not yet understand this behavior, but we suspect that it may be related to a strong tendency for the junction to generate radiation at these characteristic frequencies.

The resolution of the spectra in Figs. 1 and 2 was about 1 $cm^{-1}$. Higher resolution spectra showed complicated structure, which, for some experimental geometries, could be identified with cavity resonances in the surroundings of the junction. The conical mounting eliminated most, but not all, such structure.

We are investigating the possibility that the strong response of Josephson junctions to radiation in the neighborhood of the energy gap, $2\Delta$, is a consequence of the frequency-dependent Josephson-current amplitudes first pointed out by Riedel[7] and recently discussed in detail by Werthamer.[8]

In order to compare the response of the Josephson current to power incident at frequencies in the vicinity of the energy gap with the well-known response at lower frequencies,[3] In-In and Nb-Nb junctions were exposed to monochromatic radiation at both 2.5 and 5 $cm^{-1}$. Incident power levels at or above $10^{-8}$ W caused constant voltage steps at $V = nh\nu/2e$ which extended beyond $V = 2\Delta/2e$, and whose current amplitude varied with power in the usual way.[3]

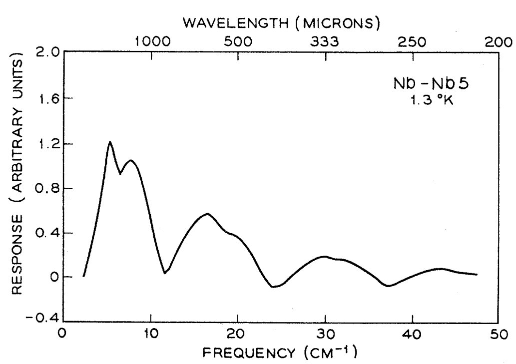


FIG. 2. Spectral response of a typical Nb-Nb superconducting point contact.

At substantially lower power levels, only the initial decrease in zero-voltage current was observed, as in the experiments using broadband radiation.

In supplementary experiments using single-frequency radiation at 2.5 $cm^{-1}$ from a klystron, the noise-equivalent power in a one-cycle bandwidth of the junction acting as a detector was measured to be $\approx 5\times10^{-13}$ W for Nb-Nb junctions. From the response curve of a Nb-Nb junction shown in Fig. 2, it is clear that the sensitivity at 2.5 $cm^{-1}$ is about a factor of 10 below the peak sensitivity which occurs at 5.5 $cm^{-1}$.

During these experiments with the klystron source, we demonstrated that the junction responded to modulation of the signal at 1 Mc/sec. This number is far below any expected inherent limit in response time. This follows from the known ability[5] of point-contact Josephson junctions to generate radiation at frequencies up to 10 Gc/sec and from their broad bandwidth as detectors as shown in Figs. 1 and 2.

Finally we have used superconducting point contacts in video detection of radiation from a second point contact. The frequency response of these junctions, as shown in Figs. 1 and 2, makes it probable that the radiation observed was at a higher frequency than in earlier experiments using point-contact or thin-film Josephson junctions as emitters.[5,9] These experiments will be reported at a later date.

To sum up, we have measured spectral response curves suggesting the existence of frequency-dependent Josephson current amplitudes peaking in the vicinity of the energy gap, we have shown that point-contact Josephson junctions respond sensitively and with high speed to millimeter and submillimeter radiation, and we have carried out experiments in which radiation emitted to free space by one such junction was detected by another junction.

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# EFFECT OF FERROMAGNETIC SPIN CORRELATIONS ON SUPERCONDUCTIVITY*

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If the superconducting transition temperatures of the transition metals are fit by the BCS relation[1]

$$T_c \sim \Theta_D \exp[-1/N(0)V_{BCS}], \tag{1}$$

where $\Theta_D$ is the Debye temperature and $N(0)$ is the density of states at the Fermi surface, then the pairing interaction $V_{BCS}$ is found to be roughly constant, except for metals at the beginning and end of each series, where it rapidly decreases.[2] Traditionally, one writes

$$V_{BCS} = V_{ph} - V_C^*, \tag{2}$$

where $V_{ph}$ represents the phonon interaction and $V_C^*$ is the Coulomb pseudopotential.[3] While at present one cannot rule out the possibility that $V_{ph} - V_C^*$ is small or negative for metals near the ends of these series, the fact that their paramagnetic susceptibility is anomalously large[4] suggests that there are strong ferromagnetic exchange forces which enhance the spin susceptibility and presumably also suppress superconductivity for singlet spin pairing, as first discussed by Doniach[5] on the basis of a phenomenological exchange interaction.

In this note we show from first principles that ferromagnetic spin correlations which arise from strong Coulomb interactions between the valence electrons lead to an enhanced singlet-state repulsion.[6] For realistic values of system parameters, this spin-induced repulsion can be many times larger than the conventional Coulomb pseudopotential. For example, in systems like Pd, whose static spin susceptibility is strongly exchange enhanced, this repulsion is sufficient to suppress superconductivity totally.

Physically, the enhanced singlet-state repulsion arises because of ferromagnetic spin polarizations induced by the interacting electrons. If the exchange interaction is nearly strong enough to produce ferromagnetic alignment, a given up-spin electron, $A$, will be surrounded primarily by electrons of up spin. Since the phonon interaction is very short range in space, a down-spin electron, $B$, attempting to lower its energy by taking advantage of the phonon attraction produced by $A$, must first pass through a large region of unfavorably oriented spins. Thus, there is an effective exchange potential barrier separating electrons of opposite spin, and if the space and time persistence of the induced spin-polarization cloud is sufficiently large, the integrated exchange repulsion can dominate the phonon attraction.

Mathematically, the effects of ferromagnetic spin correlations are incorporated into the singlet-state pairing interaction by noting that the paramagnetic susceptibility function $\chi(q,\omega)$ develops a pole in the limit that $q$ and $\omega \to 0$ at the ferromagnetic instability. This behavior is due to the singularity in the amplitude for particle-hole scattering, as is conveniently seen in the random phase approximation (RPA) form for $\chi$ shown graphically in Fig. 1(a). In the static, long-wavelength limit[7]

$$\chi_{RPA}(0,0) = \chi_P/[1-N(0)V_C], \tag{3}$$

if one assumes that the screened Coulomb interaction is zero ranged, a reasonable approximation in the narrow $d$-band metals because of the screening due to the $s$ electrons. Here, $\chi_P$ is the Pauli susceptibility. In RPA, $\chi(0,0)$ diverges when $N(0)V_C = 1$, the Hartree-Fock